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Soviet Microelectronics: Impact of Western Technology Acquisitions

An Intelligence Assessment

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December 1986

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Soviet Microelectronics: Impact of Western Technology Acquisitions

An Intelligence Assessment

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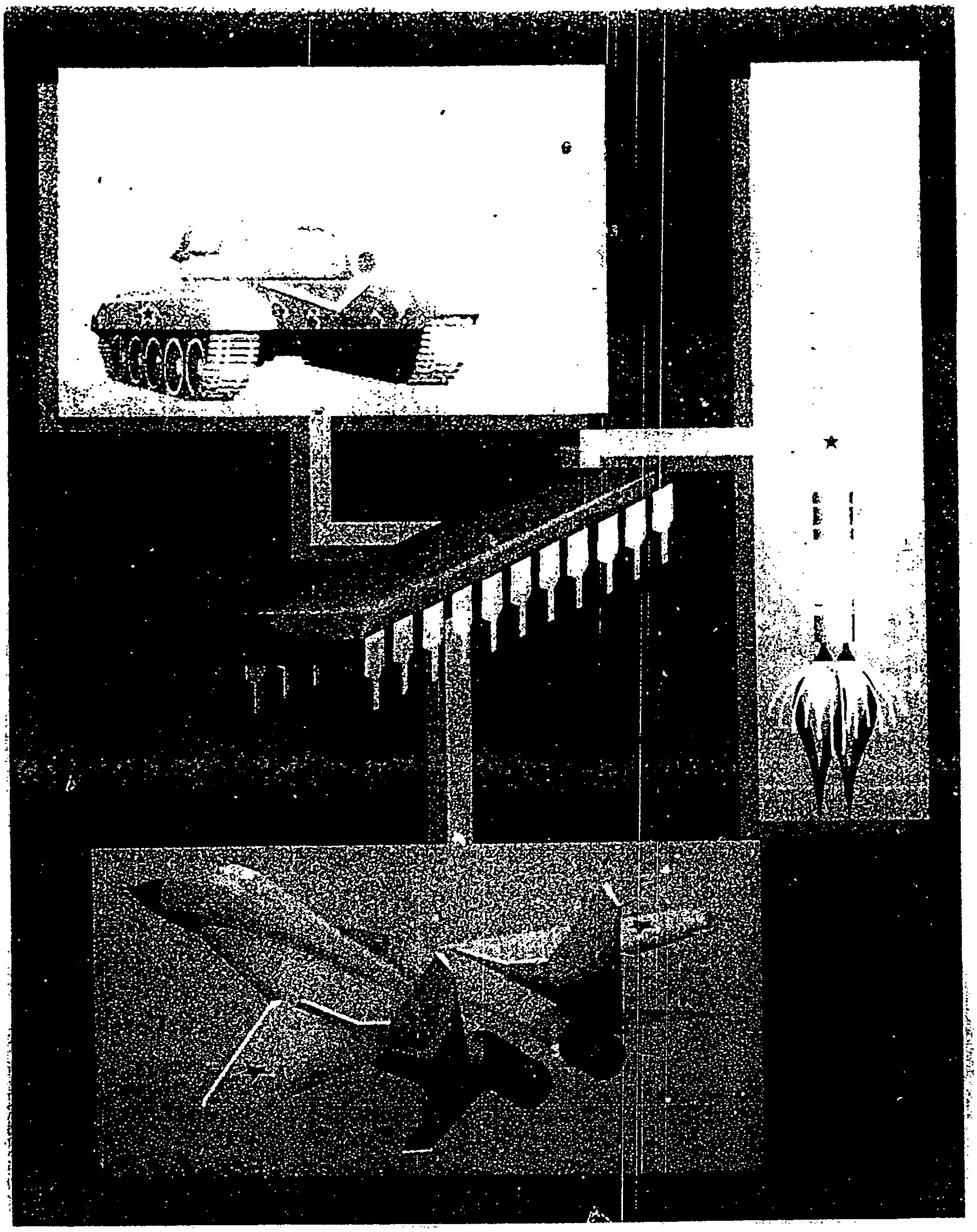

Soviet Microelectronics: Impact of Western Technology Acquisitions

Key Judgments

Information available as of 1 November 1986 was used in this report.

Soviet acquisition of Western technology has radically advanced the quality and quantity of Soviet microelectronics production:

- Without Western technology, the Soviets' lag in advanced integrated circuit (IC) development—which we estimate to be eight to nine years—would be further exaggerated, possibly by an additional decade.
- Without Western production technology, the Soviets' annual output of microelectronic devices would be reduced by up to 25 percent for discrete semiconductor devices, 75 percent for small- to medium-scale ICs, and possibly more than 90 percent for large-scale ICs.

The successful and, in most cases, illicit acquisition of Western technology has enabled the Soviet Union to meet the critical microelectronics needs of the military. We believe that the impact for Soviet military systems has been significant in the application of small- to medium-scale ICs and revolutionary in the application of large-scale ICs. Because the Soviets are more aggressive in their application of new technology to military systems than the United States, they have reduced their microelectronics technology lag in fielded military systems by approximately three to five years over the lag they would have had if they used US design philosophy. This lag reduction has been accomplished because Soviet system designers incorporate new Soviet ICs into major weapon system designs when the ICs reach pilot production in the USSR, while US system designers wait until new US ICs reach full-volume production in the United States. We believe that ICs such as 8-bit microprocessors are likely to appear now as embedded components in Soviet major weapon systems, only shortly after they appeared in US systems. Similarly, 64K dynamic random access memories are likely to appear concurrently in both US and Soviet major weapon systems in the early 1990s.

Soviet ability to produce advanced IC has enhanced the impact of other acquisitions such as the
We believe that, without microelectronics transfers, the Soviets would have had to delay initiating development of radars comparable to the F-18 radar for at least several years—possibly up to eight to 10 years—waiting for indigenous development of the required ICs

The Soviet practice of placing priority on relatively low-volume military microelectronics production versus high-volume nonmilitary production has been a two-edged sword. This prioritization has enhanced applications to military systems, but probably has delayed overall microelectronics industrial advancement. For example, Western manufacturers credit volume production for a high portion of advances in yield and production technology. Reported Soviet yields are extremely low compared with Western yields.

The Soviets' historical reliance on following many Western IC developments will also have negative repercussions on their future microelectronics capabilities. Because the Soviets have opted to rely on the West for innovation, the United States is ensured a minimum technology lead of at least two to three years and a minimum production lead of at least three to four years. Using technology transfer to adapt Western circuit designs, production equipment, and production practices, the Soviets reduced the US technology and production leads for large-scale ICs to two to three years and three to four years, respectively. This strategy has not yet produced similar progress with very large-scale ICs, and we believe that the USSR recently has begun to slip further behind because of technical problems inherent in very large-scale IC production and possibly because of Western multinational export controls. We expect that the current overall Western lead of about eight to nine years will steadily increase.

Soviet microelectronics production technology has also failed to keep pace with the West

Because of this, we estimate that, despite a large number of production facilities, Soviet output is only about 25 percent of US production of discrete devices and about 10 percent of US IC production. This low output and the Soviets' continued legal and illegal acquisition of millions of low-level ICs lead us to believe that the Warsaw Pact has an across-the-board shortage of all but the most basic ICs.

Since the early 1970s the Soviets probably have spent over $2 billion in the West for microelectronics acquisitions. The over 3,000 pieces of production equipment that we know the Soviets have acquired could outfit 24 typical Western IC fabrication areas. In addition, we believe the Soviets have illicitly acquired a significant amount of Western equipment on which there is no intelligence reporting. We believe the total amount of Western equipment acquired by the Soviets could supply as much as, but probably not more than, one-third of the critical equipment for all Soviet production areas. Because this Western equipment is more capable than its Soviet counterparts, it probably is used primarily on production lines that turn out the Soviets' most advanced ICs and would therefore represent an even higher percentage of the equipment used in these facilities. The USSR has recently been acquiring smaller numbers of more advanced and productive equipment concentrated in areas of Soviet technological weakness.

We believe that the Soviets' goals for their microelectronics industry include:

- Improvement of their very large-scale integration capabilities.
- Development of advanced very large- and ultralarge-scale integration capabilities.
- Augmentation of domestic production.
- Insertion of state-of-the-art ICs in future military systems.

To meet these goals, needed to improve performance of military systems, the Soviets will initially have to improve their clean room technology, circuit design capabilities, feature resolution, thin-film quality, and automatic testing equipment. They then will need to produce higher quality silicon and develop advanced packaging and metalization techniques. Only extensive use of Western technology will enable Moscow to achieve these goals in a timely manner

At present, we believe that the USSR is focusing a large part of its technology acquisition program on US very high-speed integrated circuit (VHSIC) development, both to advance Soviet capabilities and to assess the impact of VHSIC on US weapons. Also, in addition to the likely massive intelligence collection program the Soviets already target against the Strategic Defense Initiative (SDI), they are likely to focus significant resources on microelectronics research deriving from the SDI

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Soviet Microelectronics:
Impact of Western
Technology Acquisition

Scope Note

This assessment examines Soviet microelectronics and measures the impact of Western technology on the Soviet microelectronics industry and, in turn, on the Soviet military. On the basis of this analysis, we have forecasted Soviet microelectronics goals and the resulting technology acquisition targets in the West. This paper is the first in a series of studies on Soviet priority targets by the [redacted] Upcoming studies will address, among other topics, deepwater submersible technology, microelectronics automatic testing equipment, computer-controlled digital switching, hot isostatic press technology, and personal computer technology.

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Soviet Microelectronics: Impact of Western Technology Acquisitions

Microelectronics: Foundation Technology

Microelectronics is a foundation technology with broad application. Digital microelectronic circuits are largely general purpose in nature and are used in civilian and military systems. These circuits have several inherent qualities—complex logic, large memory, high speed, low power, small size, and high reliability—that directly impact weapon systems development, production, and operation (see figure 1). The United States and Japan continue to be world leaders in microelectronics development and production. In general, Soviet efforts lag those of the West. This paper surveys the Soviet industry, assesses the impact of Soviet acquisitions on the general technical level of the industry and on specific military systems, and projects critical Soviet needs that would prevent the gap between US and Soviet microelectronics from growing.

Soviet Capabilities and Deficiencies: Overcoming Weaknesses With Strengths

Soviet Microelectronics Infrastructure: Industrial Centers

We have located over 70 microelectronics production plants in the Soviet Union (see inset. "Growth of an Industry").

In terms of rate of increase, the Soviet building construction program for microelectronics production peaked in the early 1970s, although production floorspace has continued to grow each year. We believe that current construction probably will house the production of more advanced ICs

The slowdown in construction suggests that the Soviets may now have nearly enough production floorspace to meet their established goals or, less likely, that the Soviets are having difficulty purchasing, building, and assimilating equipment for new facilities.[1]

The center of Soviet advanced microelectronics re search, development, and production is a large co plex in Zelenograd, about 40 kilometers from Mo (see figure 2). Zelenograd is intended to be a Sovi "Silicon Valley," and includes five series-product plants, an educational institute with pilot-product lines, and at least a dozen scientific research insti tutes. Outside of Zelenograd, the most advanced production plants known are found near Leningr Kiev, and Minsk.

Microelectronics Technology: What the Soviets Can Do

The Soviets have developed a large microelectronics industry. They are able to produce a large number of ICs of various types, are strong in fundamental research, and aggressively apply new microelectronics technology to military systems (see inset, "Microelectronics Development Milestones").

Production Capability. Although the USSR produces a large number of ICs, we believe, on the basis of

per square meter of floorspace is substantially below what the US industry can achieve. If the US microelectronics industry used the Soviet production floorspace and produced the Soviet product mix with US standards and equipment, output would be about 10 times that estimated for the Soviet industry.

Soviet production capacity is based on our estimates of Soviet productio

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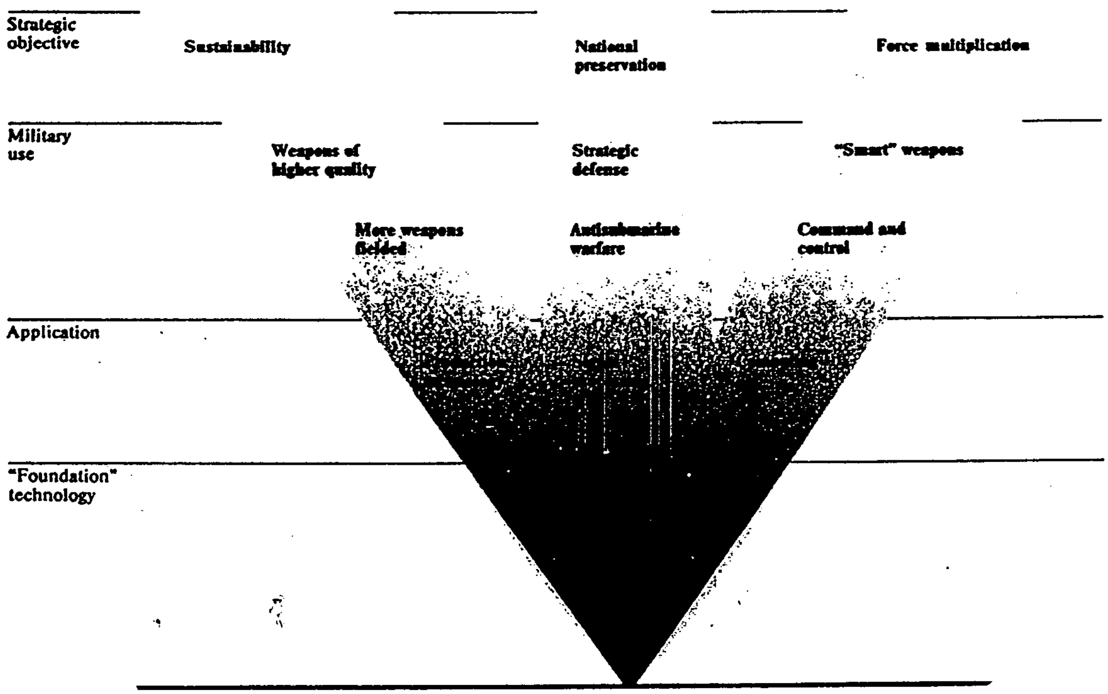
Figure 1
Examples of Military Impact of Microelectronics



most modern East European facilities. Using these estimates and a [redacted] production model, we calculate that Soviet yearly production is at most 2 billion discrete semiconductor devices, 1 billion small-scale integration (SSI) and medium-scale integration (MSI) ICs, 150 million large-scale integration (LSI) ICs, and a few hundred thousand very large-scale integration (VLSI) ICs.[2] Although these production quantities are large, they represent only about 25 percent of US production of discrete devices and about 10 percent of US IC production. Furthermore, US ICs are generally more sophisticated in the areas of circuit complexity, operating speed, reliability, and minimum feature size than those produced in the USSR.

Product Mix. According to open sources and [redacted], the Soviets have developed over 25 microprocessor types, spread across a number of technologies (TTL, STTL, ECL, IIL, nMOS, pMOS, CMOS) and system architectures. These include 2-, 4-, 8-, and 16-bit word-length microprocessors, which by Western standards would be first (for example, 4-bit Intel 4004), second (for example, 8-bit Intel 8080),

[2] We will describe the sophistication of Soviet microelectronic devices as follows. Discrete devices include individual transistors and diodes. SSI and MSI ICs are generally logic devices that perform simple, nonprogrammable functions or store up to 1,000 bits of data. LSI ICs include 8- and 8/16-bit microprocessors and dynamic random access memories from 4K to 64K. VLSI includes 32-bit microprocessors and 256K and larger DRAMs

Growth of an Industry

The world microelectronics industry began in earnest in the early 1960s with production in the United States of the first integrated circuits (ICs). The Soviets recognized the immense impact microelectronics would have, particularly on military capabilities. In part because their initial research paths soon left them far behind US developments, Moscow reorganized its microelectronics effort and created the State Committee for Electronic Technology (GKET), which in 1965 became the Ministry of the Electronics Industry (MEP;

The MEP is the principal ministry responsible for research, development, and production of electronic components and subassemblies—including diodes, transistors, capacitors, resistors, vacuum tubes, ICs, acoustic devices, optoelectronics, bubble memories, and magnetic cores. The MEP also develops materials processing, engineering instrumentation, and production technologies. Our analysis of [redacted] *and trends in the industry suggests that the MEP currently employs several hundred thousand workers. The MEP, as one of nine defense industrial ministries, devotes well over half of its output to military or defense industry uses.*

The MEP is not the only Soviet source of microelectronics devices, however. Other industrial ministries develop and manufacture small quantities of special-purpose ICs—roughly analogous to the application-specific integrated circuits (ASICs) manufactured in the West. Other ministries that develop and produce ICs include the Ministry of the Radio Industry; Ministry of Instrumentation, Automation, and Control Systems; Ministry of the Communications Equipment Industry; Ministry of General Machine Building (space and missiles); and the Ministry of the Defense Industry (armor and electro-optics). These ministerial production programs probably reflect efforts to avoid excessive dependencies on other ministries, concerns that the MEP will not be able to meet quality-quantity demands on timely schedules, and recognition that the MEP can resist developing and manufacturing products in quantities that it considers insignificant

and low-level third generation (for example, 16-bit Intel 8086) microprocessors. Future Soviet circuits will probably compare to high-level third (for example, 16-bit Motorola 68000) or current fourth generation (for example, 32-bit Motorola 68020) microprocessors produced in the West. The Soviets have indicated their intentions to use these devices in minicomputers planned for series production about 1990.

A higher percentage of these Soviet ICs than would be considered normal in the West (50 percent versus 10 percent) are of bit-slice design. Bit-slice microprocessors can be combined to construct multiple-chip microprocessors with a larger word length. They are less advanced than equivalent single-chip microprocessors but can offer comparable performances, although with penalties in size and power consumption. These factors (variety of production technologies and word lengths plus the large percentage of bit-slice designs) all combine to offer the USSR a wide variety of microprocessor options, although not optimized for each application to the extent possible in the United States with its much larger variety of microprocessors

In IC memory technology, the Soviets have produced dynamic random access memories (DRAMs) up to the 64K level. As with microprocessors, the Soviets have spread their memory ICs across several technologies. [redacted] indicate the Soviets are attempting to improve low production yields for 64K DRAMs, which achieved full-volume production in about 1984. [redacted] report that the Soviets have begun initial series production of a 256K DRAM

Research. In terms of fundamental research—carried out by the Academies of Science and technical universities—we believe that Soviet efforts are generally equal to those in the West. Research into materials, physics, chemistry, and transistor or diode structures sometimes surpasses US advances. For example, according to US industry assessments, Soviet research and development on negative-electron-affinity (NEA) devices—used almost exclusively for military night-vision applications—is moving beyond the United

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States in some areas, although the Soviets lag substantially in production and application of these devices. Also, Soviet work on superconducting magnetic flux detectors (used for antisubmarine warfare), superconductor-insulator-superconductor devices, and Josephson mixers is of good quality and has frequently anticipated Western work. In applied research—feasibility demonstration—the Soviets also use innovative design practices to bypass production limitations

Application. The Soviets' structured, controlled organization enables them to apply their limited microelectronics development resources directly toward military production. The Soviets more aggressively apply new microelectronics technology to military systems than does the West. For example, new ICs are designed into developing military systems and critical computer products when the ICs reach pilot production. In the design stage, a system is then about eight to 10 years from completion, so Moscow has that time to achieve full-volume production of the IC—a limit the Soviets have easily been meeting. Meanwhile, pilot production quantities (a few hundred per year) are adequate for Soviet system developers to use in hardware prototyping and testing. In the United States, military systems designers do not usually incorporate ICs into designs until full production of the chips is achieved. There are some isolated exceptions to this US practice

Microelectronics Development Milestones

We divide Soviet microelectronics production into three development milestones: pilot production, initial series production, and full-volume production. Pilot production *is achieved at a design bureau and is characterized by the demonstration of a functioning production process, with integrated circuit (IC) production in the hundreds per year. Production is then transferred to a full-scale microelectronics production plant, where the knowledge developed at the design bureau is used to outfit a production line and to begin* initial series production *by starting the first wafer through the line. At this stage, IC production averages in the thousands per year. As the production plant refines its technology, yields improve until they reach an upper limit dictated by the quality of the equipment and the workers' expertise. When the yields approach this limit,* full-volume production *is reached, no matter how low this yield limit might be. In the USSR, full-volume production of ICs is typically 100,000 per year or greater. In the United States, technology is developed in much the same way, although the production quantities for similar ICs are in the hundreds for pilot production, tens of thousands for initial series production, and 1 million or greater for full-volume production. In the United States these milestones may be achieved by an individual nonmerchant firm such as IBM, even though the circuits are not widely available from commercial firms such as Intel or Motorola.*

Microelectronics Technology: What the Soviets Cannot Do and How They Compensate

Although the USSR is strong in fundamental research and aggressive application, its greatest weakness lies in production of microelectronics, especially advanced ICs.

Problems Resulting From Technical Weakness. On the basis of the aforementioned sources and our own exploitation of Soviet ICs, we believe that, although the Soviets have made major improvements in recent years, they still face chronic problems related to quality control. The Soviets have production problems primarily in the areas of lithography, etching, and testing. They also have difficulty in the general area of process control—getting the production lines to work as specified. We believe that limited Soviet computer-aided design (CAD) capabilities hinder the development of both new ICs, such as 32-bit microprocessors, and advanced or improved versions of current ICs, such as 16-bit microprocessors and peripherals

Problems Resulting From Industrial Practices. The Soviet practice of placing priority on relatively low-volume military production versus high-volume nonmilitary production has been a two-edged sword. It has enhanced applications to military systems, but has probably delayed overall industrial advancement. For example, Western manufacturers credit volume production—spurred by vast commercial opportunities—for a high portion of advances in yield and production technology. Statistical studies of process variations in huge production runs enable problems to be quickly identified and solved. When the military production focus is combined with the generally lower quality of Soviet production equipment and process control, we conclude that these factors significantly hamper Soviet capabilities to increase product yields. , Soviet IC production yields are extremely low compared with Western yields. ICs such as 64K DRAMs are produced in the USSR with yields—the percentage of functioning ICs—well under 10 percent. In the United States these ICs would be produced with yields of about 60 to 70 percent.

Using a strategy of adapting Western technology, the USSR has saved a tremendous amount of research and development resources that would otherwise have been required to achieve similar results. The Soviets' historical reliance on following many Western IC developments also has some negative repercussions on their microelectronics capabilities. The Soviet policy of relying largely on Western technology for innovation ensures a US applied technology lead in pilot production of at least two to three years. This is the minimum time required for the Soviets to adapt a US IC and achieve pilot production. Soviet weakness in volume production ensures that the United States will remain at least three to four years ahead in series production capability.

Technology Lag. To measure the relative technological capabilities of the United States and the USSR, we compare US initial series production to Soviet initial series production and US full volume to Soviet full volume. We believe that the Soviets made their closest approach to US DRAM milestones in initial series production with their 16K, 64K, and 256K DRAMs, cutting the US lead to two years between 1976 and 1983. For full-volume DRAM production we believe that the Soviets made their closest approach to US milestones with their 16K and 64K DRAMs, cutting the US lead to three years between 1978 and 1981. Soviet initial series production matched—with some time delay—the US rate of progress from 16K to 256K. We believe, however, that they have begun to slip back in volume production for 256K and in the development of next generation chips.[3]

Although the Soviets quickly advanced to the LSI level, the transition to VLSI-level production has been slow. Two factors may have contributed to this: technical problems inherent in VLSI IC production, including a lack of suitable production buildings, and Western multinational export controls. The trends for DRAMs and microprocessors are shown in figure 3 and table 1 and figure 4 and table 2. US industry is producing 32-bit microprocessors in full volume, and deliveries of 1-megabit DRAMs are under way. We do not anticipate Soviet full-volume production of equivalent devices—enabling them to satisfy full military and industrial consumers' demands—much before the period 1994-95 for either type of device. We therefore assess the current US lead in volume production at about eight to nine years and increasing.

[3] The USSR has been cooperating with Eastern Europe and especially East Germany in developing advanced IC technology.

The preceding argument focuses on the qualitative aspects of the US lead by comparing the dates at which technological milestones have been or will be reached. The quantitative aspects of US versus Soviet capabilities are also important. Even though evidence and analysis indicate that the Soviets probably achieved full-volume production of 64K DRAMs and 16-bit microprocessors during 1983-84, we do not believe the Soviets' production meets their needs for these devices. In the West, the time between volume production and general availability is about one year. Because we still observe the Soviets trying to buy large volumes of 16K DRAMs and 8-bit microprocessors—both of which are LSI ICs that went into full-volume production in the USSR in 1981—we believe it is unlikely that they have adequate supplies of these or more sophisticated ICs. Judging from the continued legal and illegal acquisition of millions of Western low-level SSI and MSI ICs, we believe that the Warsaw Pact has an across-the-board shortage of all but the most basic ICs such as standard TTL NAND, AND, OR, and NOR logic gates; or J-K or D flipflops. It is difficult to assess the military impact of this shortage because the Soviets satisfy military requirements first, leaving industrial applications to feel the pinch. However, the inadequate supply of ICs prevents the Soviets from fully building up sectors such as industrial process control and educational computers with indigenous products.

Compensating for Technology Lag. Nonetheless, from the military's view, this scenario, while not ideal, could be sufficient when combined with the Soviets' aggressive practice of incorporating new microelectronics technology into weapon systems on the basis of pilot production instead of full-volume production. The impact of the Soviet philosophy of aggressive application is shown in figures 5 and 6, in which Soviet pilot production milestones are compared with US full-volume production milestones.

This impact is apparent with the 64K DRAM and 8-bit microprocessor [ ] indicate that the Soviets demonstrated pilot production of a 64K DRAM probably in 1980, while the United States achieved full series production in 198[ ] that the Soviets demonstrated pilot production of an 8-bit microprocessor copy of the Intel 8080 in

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Figure 3
Microprocessor Production Milestones, US Versus USSR

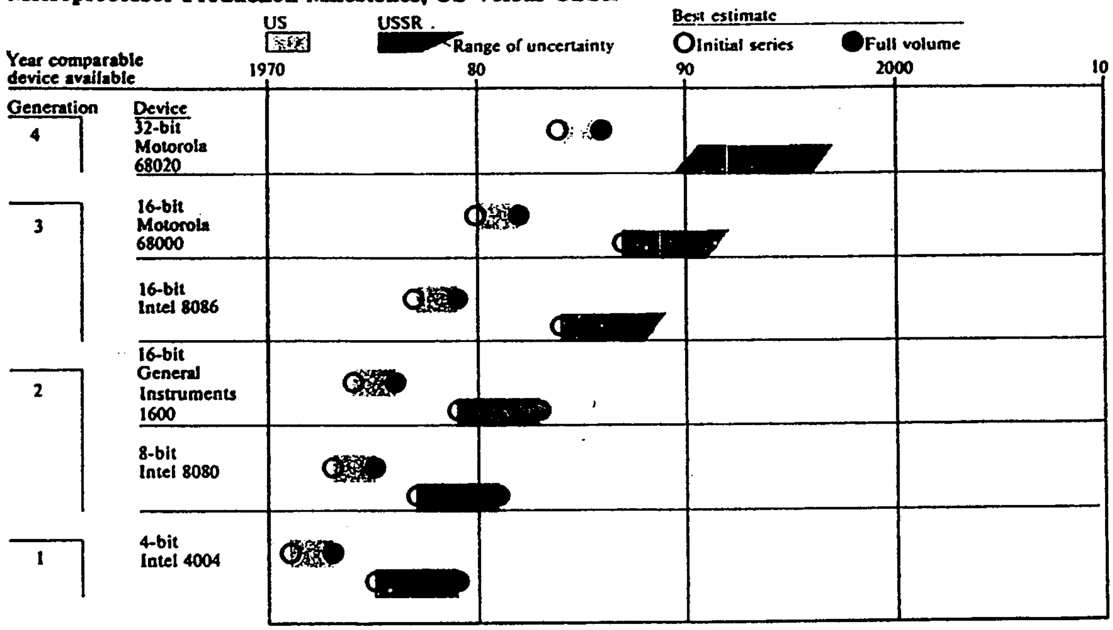

Figure 3 shows the dates the United States and the USSR first achieved initial series production and full-volume production of various types of microprocessors (see text box for definitions of these milestones). Microprocessor type is defined by word length, although this measure is necessarily vague because complex microprocessors often have inconsistencies in their internal word length. We have therefore related the various types of microprocessors to a US standard chip for which the Soviets have developed (or probably will develop) a counterpart. It should be noted that Soviet ability to produce a counterpart does not imply that the Soviet part matches the performance of the US original—in fact, Soviet microprocessors seldom approach the performance of US counterparts.

Table 1
US Lead Over the USSR in Comparable Microprocessors [a]

	Year	Device Type	Lead *(in years)*		Year	Device Type	Lead *(in years)*
Initial series	1971	4004	4	Full volume	1973	4004	6
	1973	8080	4		1975	8080	6
	1974	1600	5		1976	1600	7
	1977	8086	7		1979	8086	9 (+1−1) [b]
	1980	68000	7 (+1−0) [b]		1982	68000	9 (+1−1) [b]
	1984	68020	7 (+2−1) [b]		1986	68020	9 (+2−1) [b]

[a] This table shows that the US lead over the Soviet Union for initial series and full-volume production of microprocessors has been slowly increasing since the early 1970s and is likely to remain steady or increase in the future. This lead is based on the first US and Soviet achievement of these milestones for microprocessors that the USSR has copied (or will probably copy) from US originals. These Soviet copies, however, seldom approach the performance of the US original.

[b] Projection based on expected Soviet development.

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Figure 4
DRAM Production Milestones, US Versus USSR

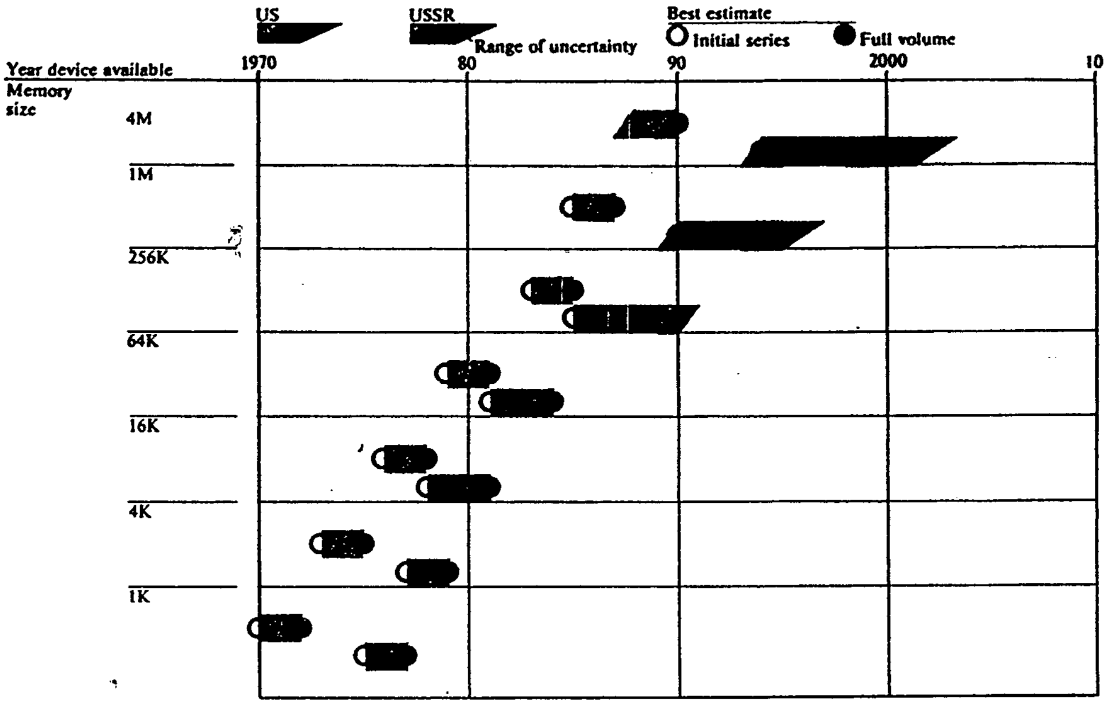

Figure 4 shows the dates the United States and the USSR first achieved initial series production and full-volume production of various types of DRAMs (see text box for definitions of these milestones). DRAMs are defined by capacity, with 1K equal to 1024 bits of binary data stored. The speed at which these DRAMs operate (their access time) and their soft error rate also contribute to the measure of DRAM sophistication, although because of complexity we have ignored these factors. It should be noted that Soviet ability to produce a similar capacity DRAM does not imply that the Soviet part matches the performance of the US model—in fact, Soviet DRAMs seldom approach the access time or soft error rate of US chips.

Table 2
US Lead Over the USSR in DRAMs [a]

	Year	Memory Size	Lead *(in years)*		Year	Memory Size	Lead *(in years)*
Initial series	1970	1K	5	Full volume	1972	1K	5
	1973	4K	4		1975	4K	4
	1976	16K	2		1978	16K	3
	1979	64K	2		1981	64K	3
	1983	256K	2		1985	256K	5 (+1−1) [b]
	1985	1M	5 (+1−1) [b]		1987	1M	8 (+3−2) [b]
	1988	4M	6 (+3−1) [b]		1990	4M	10 (+4−2) [b]

[a] This table shows that the US lead over the Soviet Union for initial series and full-volume production of DRAMs reached a minimum in the late 1970s and early 1980s and has been rapidly increasing since then. This lead is based on the first US and Soviet achievements of these milestones for DRAMs of the same memory capacity. These Soviet DRAMs, however, seldom approach the access time or soft error rate of US models.

[b] Projection based on expected Soviet development.

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Figure 5
Dates Comparable Microprocessors Available to Weapons Systems Designers

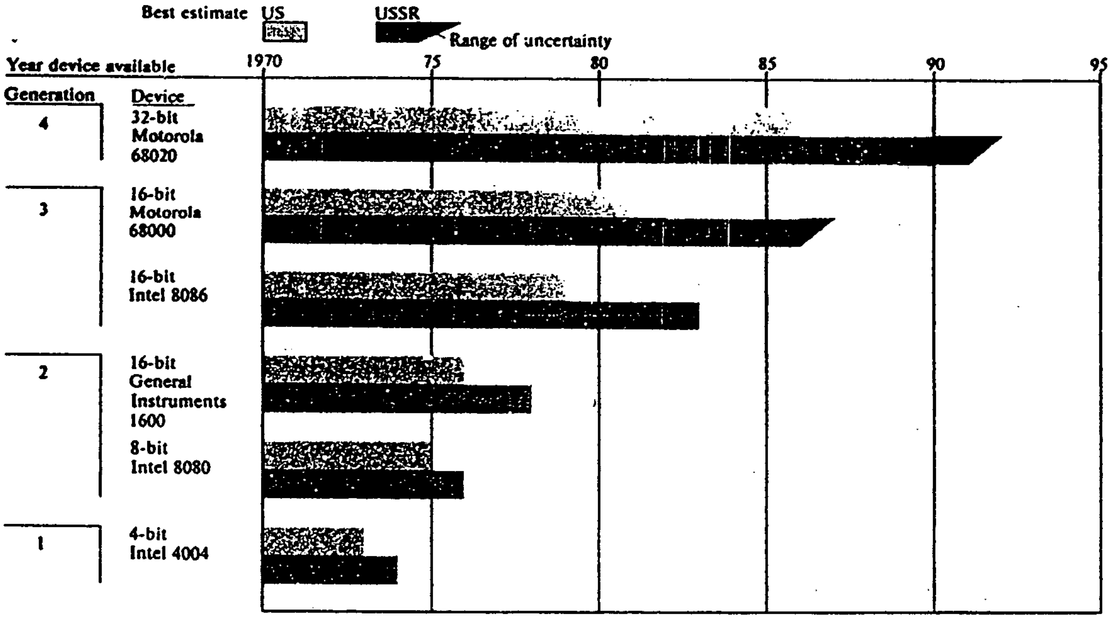

Figure 5 shows US full-volume production milestones compared with Soviet pilot production milestones for specific US microprocessors copied by the USSR. US and Soviet major military systems designers use these milestones to decide which ICs are available for weapons designs. For both the United States and the USSR, major systems will be fielded with these microprocessors eight to 10 years after these dates. Using their aggressive application philosophy, the Soviets have reduced their microprocessor technology lag in fielded military systems by approximately five years over the lag they would have if they used US design philosophy.

1976, while the United States achieved full series production in 1975. Because both the United States and the USSR require eight to 10 years to field a major weapon system once the embedded IC technology is selected, 64K DRAMs are likely to appear concurrently as embedded components in both US and Soviet major weapon systems in the early 1990s. Similarly, 8-bit microprocessors are likely to appear now in Soviet systems, only shortly after they appeared in US systems. We conclude that, by using this aggressive application philosophy, the Soviets reduced their microprocessor technology lag in fielded military systems by approximately five years over the lag they would have had if they used US design philosophy.

The Soviets have reduced their DRAM technology lag by three to five years over the lag they would have had if they used US design philosophy

Soviet Technology Acquisition Strategy: Using the VPK and Foreign Trade

The Soviet effort to acquire Western microelectronics equipment has two overlapping parts. One is a program managed by the Soviet Military Industrial Commission (VPK) of the Presidium of the Council of Ministers. The other is a trade diversion program

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Figure 6
Dates DRAMs Available to Weapons Systems Designers

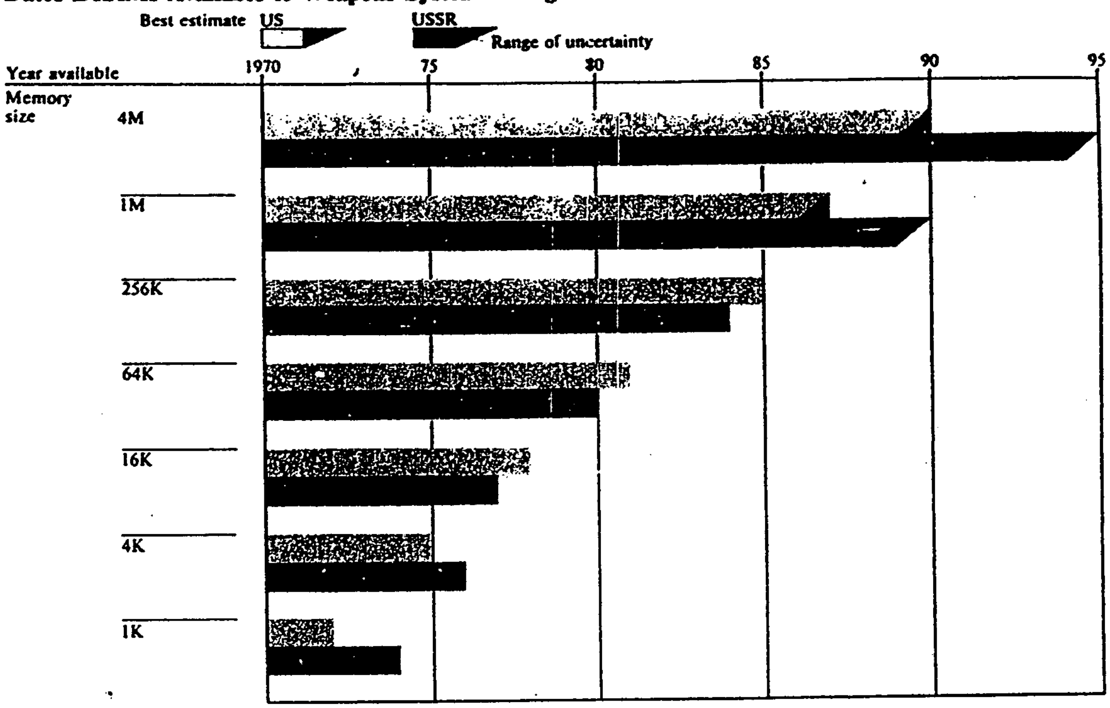

Figure 6 shows US full-volume production milestones compared with Soviet pilot production milestones for similar capacity DRAMs. US and Soviet major military systems designers use these milestones to decide which ICs are available for weapons designs. For both the United States and the USSR, major systems will be fielded with these DRAMs eight to 10 years after these dates. Using their aggressive application philosophy, the Soviets have reduced their DRAM technology lag in fielded military systems by approximately three to five years over the lag they would have if they used US design philosophy.

managed by the Ministry of Foreign Trade (MFT). Both these programs have been successful. Through both legal and illegal trade, since 1972 the Soviets have acquired at least 3,000 pieces of major microelectronics fabrication equipment covering the entire spectrum of production operations (see appendix). We believe the Soviets have spent over $2 billion in the West on microelectronics acquisitions since the early 1970s.

VPK Acquisitions: Improving Performance of Military Systems

The VPK program seeks, primarily through intelligence channels, one-of-a-kind military and dual-use hardware, blueprints, product samples, and test equipment to improve the technical levels and performance of Soviet weapons, military equipment, and defense manufacturing equipment. Most of the microelectronics-related requirements originate from the Ministry of the Electronics Industry (MEP). In addition, other ministries conduct studies with the MEP or issue separate requirements on microelectronics-related acquisitions, although on a much smaller scale. The principal ministries involved are the Ministry of the Radio Industry, the Ministry of the Communications Equipment Industry, the Ministry of General

Machine Building (space and missiles), and the Ministry of the Defense Industry (armor and electro-optics). In the late 1970s the MEP alone originated almost one-third of all VPK requirements (almost all of these MEP requirements were in the microelectronics area), demonstrating the high priority the Soviets place on microelectronics.

the Soviets have realized many benefits from the VPK program. Many Soviet microelectronics plants have established programs to reverse engineer US production equipment. They have been particularly successful in adapting proven Western designs and incorporating the Soviet adaptations into production lines. Between one-third and one-half of all identified Soviet microprocessors are known to be adapted from US versions:

Soviet Part	US Part
K145, K532, K536	...[a]
K555	Possibly based on Texas Instruments SN74LS481
K580	Intel 8080
K581	General Instrument 1600
K582	Texas Instruments SBP0400
K583	...[a]
K584	Texas Instruments SBP0400
K585	Possibly based on Intel 3000
K586, K587, K588	...[a]
K589	Intel 3000
K1800	Motorola 10800
K1801, K1802, K1803	...[a]
K1804	Advanced Micro Devices 2900
K1808, K1809	...[a]
K1810	Intel 8086
K1811, K1814, K1816, K1820, K1883	...[a]
...[b]	Intel 8085, Intel 8088
...[b]	Motorola 68000

[a] No *identified* US counterparts.
[b] We believe the Soviets have a version of these US parts (or soon will), but we have not yet identified the Soviet part numbers.

Much of the manufacturing equipment acquired is also intended for use in developing Soviet counterparts. Some of the significant MEP acquisitions are shown in the inset on page 13

Trade Diversion Acquisitions: Increasing Industrial Efficiency

The trade diversion program is comparable to the VPK program in scope but is characterized by illegal and legal acquisitions of relatively large numbers of dual-use products. This program, apparently managed by the MFT's Main Engineering and Technical Administration (GITU), probably is less structured than the VPK program, but is just as rigidly monitored because of the large amounts of hard currency necessary.

We believe, on the basis of our analysis and of reported Soviet acquisitions, that the dual-use microelectronics equipment known to have been acquired by the Soviets since 1972 would be sufficient to equip approximately 24 typical Western fabrication areas, each with 10,000 square feet of floorspace. This amount represents about 5 percent of all identified floorspace for Soviet wafer processing. The Soviet acquisitions we have observed, however, are certainly far below the total actually acquired by the Soviets. we believe that the actual number of acquisitions might provide as much as, but probably not more than, one-third of the critical equipment for all current Soviet microelectronics fabrication areas.

, we believe that, in the past, the microelectronics diversion program has concentrated on the acquisition of raw materials, production equipment, and ICs for direct use:

- High-purity raw materials such as silicon have primarily originated in the United States, West Germany, and Japan and have been diverted mostly through Europe.

Significant MEP Acquisitions in the Late 1970s and Early 1980s

- *Intel 8086 microprocessors and documentation, Motorola 10800 series microprocessors, RCA 1802 microprocessors. 550,000 rubles. (Ruble amounts listed here are Soviet estimates of savings.)*
- *Texas Instruments TIB0203 magnetic bubble memory and documents on the production of gadolinium-gallium-garnet substrates. 600,000 rubles.*
- *Papers of a conference on integrated optics, detailing the status and future developments in that area. 600,000 rubles.*
- *TRW TDS-1007, 1014, and 1021 analog to digital converters. 500,000 rubles.*
- *Fairchild IC testers (Sentry-VII and Xincom 5581). 4 million rubles.*
- *Advanced Micro Devices 2900 series microprocessors. 300,000 rubles.*
- *Intel 2147 memories. 350,000 rubles.*
- *Research report on field-effect transistor noise. 2 million rubles.*
- *Data from a report on growing gallium arsenide. 320,000 rubles.*
- *Mask making equipment and a report on microlithography. 1.3 million rubles.*

- Production equipment technology is primarily of US origin. Acquisitions, however, have occurred in Europe, Japan, and the United States and have moved mainly through European countries or through traditional non-European transit ports such as Hong Kong and Singapore.
- ICs intended for direct use are usually acquired by trading firms in neutral countries and then shipped in huge numbers to a Bloc destination. We estimate that up to 100 million ICs may be shipped in this manner each year. A frequently noted technique is the mix of controlled ICs with a large shipment of uncontrolled ICs.

Recently, however, Soviet acquisition priorities for microelectronics production equipment may have changed slightly. On the basis of we assess that the overall rate of reported acquisitions from all Western sources has fallen from an average of about 260 pieces per year between 1972 and 1982 to about 180 per year between 1983 and 1985. The specific types of equipment reported to have been acquired suggest that the acquisition rate has fallen by almost 50 percent in the areas of material preparation, doping, and packaging. For oxidation, lithography, and etching equipment the rate has fallen only slightly. It has remained constant in test equipment (see figure 7). We doubt that the overall drop in reported acquisitions is because of a drop in US collection efforts; technology transfer collection has been given a higher priority in recent years compared with that assigned during the 1970s.

These acquisition trends are consistent with our assessment of Soviet progress in overcoming technological deficiencies. Although the Soviets still have some problems with material preparation, doping, and packaging, in recent years these problems have lessened. In contrast, reliable sources indicate that problems with advanced lithography, etching and automatic test equipment have continued

We believe, however, that the redirection of acquisition effort alone does not explain the drop in the overall acquisition rate. Other factors probably also at play are:
- Western multinational export controls.
- A Soviet trend toward acquiring smaller numbers of more advanced and more productive fabrication equipment

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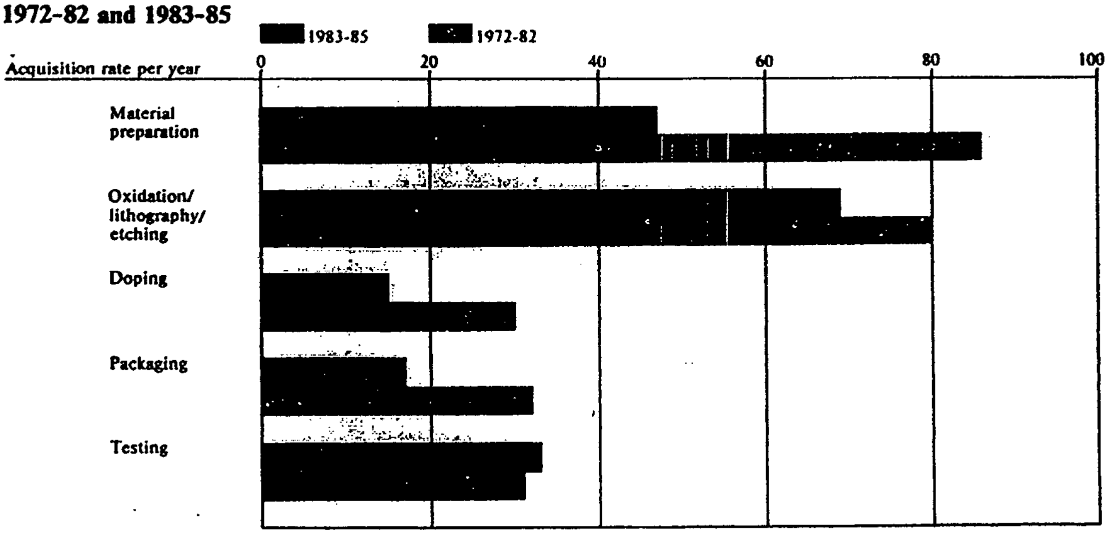
Figure 7
Average Soviet Acquisition Rate of Microelectronics Production Equipment, 1972-82 and 1983-85



Impact of Soviet Microelectronics Acquisitions: Industrial and Military Gains

Impact on the Microelectronics Industry: Significant Qualitative and Quantitative Gains

Because of access to Western technology, the Soviet microelectronics industry has made significant qualitative and quantitative gains. The qualitative impact has been the acceleration of the development of new ICs either indigenously or through reverse-engineering of Western ICs. The quantitative impact has been the improvement of production technology and increased output

Qualitative Impact on Soviet Microelectronics. To assess the qualitative impact, we have constructed a model to estimate the difference between actual Soviet technological progress and hypothetical progress in which the Soviets would rely solely on indigenous development. The model assumes that, while the Soviets would be aware of, and perhaps motivated by, Western developments, they would not use technology transfer as a method of matching or surpassing the West. Under this hypothesis, however, we would expect that the Soviets would have access to unclassified scientific information. This method results only in a rough approximation with a large uncertainty factor but does give an order of magnitude—measured in years—for the Soviet gains resulting from technology transfer

We have chosen to model the dynamic random access memory (DRAM) because it has been the technology-driving engine of the microelectronics industry. DRAMs have been key to microelectronics production technology because their simple and repetitive circuit design allows processing technology to be the main limiting factor, instead of circuit design or interconnections. The model has only two defining

assumptions:
• The rate of US progress represents a "best case."
• The Soviets' rate of progress would be less than the best case because of the inherent small size of the industry and its military focus.

We modeled hypothetical Soviet performance from the 1K DRAM through the 4-megabit DRAM level of development. To establish a starting point for the model, we estimated the time the Soviets saved by using Western technology and added it to the actual date the Soviets achieved initial series production of 1K DRAMs. On the basis of our judgment of Soviet IC development, we estimate that the Soviets saved at least four years by the time they reached the 1K DRAM milestone. Adding this to the Soviets' 1975 1K DRAM initial series production milestone, we established 1979 as the point when the Soviets would have achieved series production without Western technology. From 1979, using the US progress presented in figure 4, we established the best case rate of progress. Because of the relatively small size of the Soviet industry and its low-volume military focus, we added time to each development milestone—ranging from one year for simple circuits to four years for complicated VLSI circuits. On the basis of our understanding of endemic Soviet difficulties in precision production processes, we estimated in a similar fashion the time required for the Soviets to move from initial series production to full-volume production—that is, we added one or two years, depending on IC sophistication, to the time required by the United States. A comparison of actual Soviet performance with technology transfer and without, as estimated by this model, is presented in figure 8. Figure 9 shows the resulting estimate of the time savings from technology transfer that the Soviets realized at each development milestone.

The estimate suggests that by 256K DRAM initial production—the most recent milestone the Soviets have reached—the USSR saved as much as 14 years in cumulative development time by following a technology transfer strategy. Overall, the estimate formulated from our model indicates that actual Soviet development with technology transfer has progressed more rapidly than would have been possible without technology transfer.

It is important to note, however, that this estimate does not account for potential Soviet reaction to an increasingly widening technological gulf. For example, we do not believe the Soviets would have passively accepted a 17- to 20-year US lead in 256K DRAM development. Indeed, far smaller US leads have prompted and perpetuated Soviet technology acquisition efforts. Even without Western technology, the requirement to keep pace with Western developments in such a fundamentally important technological area would be likely to result in a more aggressive indigenous effort, such as a crash development program. For these reasons, it would be incorrect to assume that this estimate represents the effect of perfect export controls and their perfect enforcement.

Current Soviet efforts, which rely heavily on following Western efforts, lack the innovation and corporate memory on which indigenous developments build. To achieve the US best case rate of progress without using technology transfer, the Soviets would probably need to increase the size of their industry, develop a much larger consumer-industrial demand for microelectronics, and permeate their microelectronics production industry with competitive incentives.

Quantitative Impact on Soviet Microelectronics. The quantitative impact of technology transfer on Soviet microelectronics is more difficult to assess that the qualitative aspects. The acquisition of Western manufacturing technology has allowed the Soviets to increase their yield and gross throughput figures. By copying Western equipment designs, following Western manufacturing procedures, and actually using Western equipment on many production lines, the Soviets have been able to produce many more devices than would have otherwise been possible.

As stated in the "Production Capability" section of this paper, we believe that the upper range of Soviet production is 2 billion discrete devices, 1 billion SSI/MSI-level ICs, and 150 million LSI ICs. Production of discrete devices, however, does not generally require advanced equipment. The only significant advantage technology transfer would offer would be

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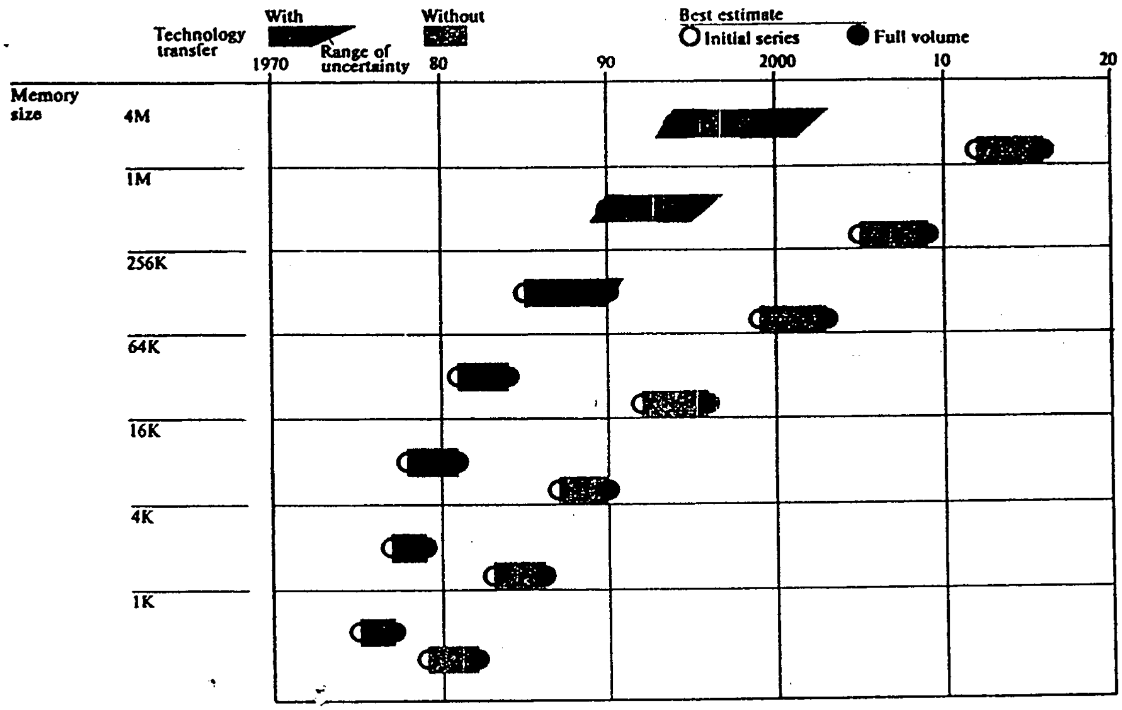
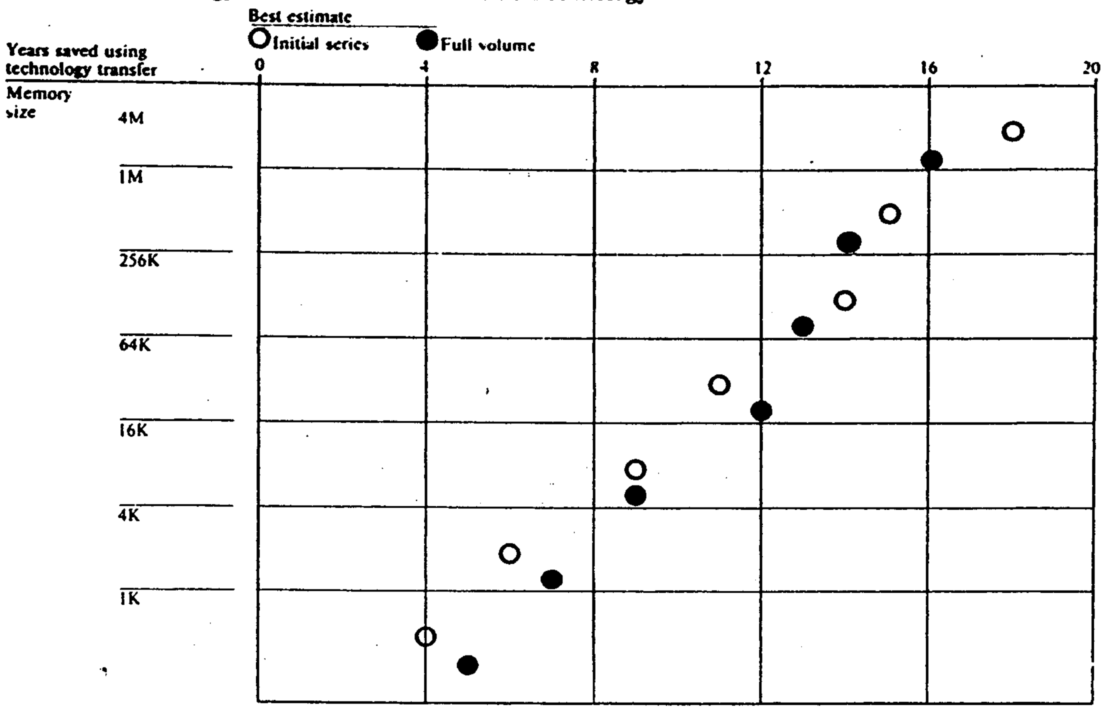
Figure 8
Soviet DRAM Technology Milestones



in production procedures, affecting production yields. On the basis of our judgment of Soviet abilities and the relative ease in production of discrete devices, we believe that this would reduce production by no more than 25 percent, reducing output to 1.5 billion. We do not believe that the increase in discrete device production resulting from technology transfer has significantly improved Soviet military capabilities.

In contrast, we believe that the increase in SSI/MSI production resulting from technology transfer has significantly increased Soviet military capabilities. Production of SSI/MSI-level ICs requires some relatively advanced equipment and production procedures. For example, without Western equipment for direct use or for use as models in developing Soviet adaptations, we believe, on the basis of engineering judgment, that the Soviets might have been unable to adequately supply up to 50 percent of their current production lines. Furthermore, we believe that the Soviets' production yields might have dropped in value by as much as 50 percent of the value now achieved because their equipment would not function as well without Western technology. These effects multiply, resulting in as much as a 75-percent reduction in production, reducing output of ICs from today's assessed annual production of 1 billion to 250 million. This reduction would have had an impact on Soviet military programs, preventing the insertion of the relevant technology into a significant number of military systems

Figure 9
Impact of Technology Transfer on Soviet DRAM Technology



The military impact of LSI production is even more significant. Production of LSI-level ICs requires advanced equipment substantially different from hardware for discrete or SSI/MSI-level circuits. Without Western equipment for direct use or for use as models, we believe, on the basis of engineering judgment, that the Soviets might have been unable to supply up to 90 percent of their current production lines. Furthermore, we believe that their production yields might have dropped in value by as much as 75 percent of the value now achieved, if their equipment had not been upgraded with Western technology. These factors would have resulted in a huge reduction in production, reducing potential output from 150 million to only a few million. At this output level, LSI ICs would have been available for only a few of the highest priority weapon systems. These judgments lead us to believe that the increase in LSI production resulting from technology transfer has revolutionized Soviet military capabilities, particularly in areas that require sophisticated signal processing and computing capabilities, such as the next generation of Soviet fighters with upgraded lookdown/shootdown radars.

Impact on Soviet Weapon System Effectiveness and Reliability: Closing the Technology Gap
Without Western technology the Soviet Union could not have developed, either qualitatively or quantitatively, the microelectronics industry at its current

pace. These improvements in the Soviet microelectronics industry have enhanced Soviet military capabilities. In general, the use of advanced ICs in military systems has several advantages:

- Computing power may be included in weapons, improving accuracy and lethality.
- Computing power may be enhanced in a wide variety of weapon platforms, sensors, and communications systems—improving major subsystems and overall performance.
- As more compact and capable ICs are used, less weight and power are required to achieve the same functions, which allows weapon payloads, military performances, and reliabilities to be increased.
- There are tremendous gains to be derived in "force-multiplier" options—allowing greater flexibility in weapons application, as well as increased system survivability.

For the Soviets, the ability to produce advanced ICs has promulgated the impact of other acquisitions

For example, the Soviets would be unable to upgrade existing lookdown/shootdown radars on their newest fighter aircraft to field multimission radars comparable to the AN/APG-65 radar used on the F-18 without low-level LSI microelectronics technology. This type of radar relies on digital electronics to:

- Achieve extremely fast data-processing rates to compensate for closing rates up to 1 mile per second.
- Allow variable waveform flexibility to achieve all-aspect/all-attitude target detection capability.
- Store and process large amounts of data to allow high-resolution/low-clutter ground mapping.

Radars that use hard-wired electronics instead of a programmable digital signal processor with large semiconductor memory capacity are unable to perform all of these functions, given the volume, power, and weight limitations on a fighter aircraft.

Although the Soviets have not yet fielded a counterpart to the US F 18 radar -

-without microelectronic transfers the Soviets would have had to delay initiating development of comparable radar systems for several years—possibly up to eight to 10 years—waiting for indigenous development of the required ICs. In addition to lookdown/shootdown radars, other current or forthcoming Soviet systems or subsystems that probably have benefited significantly from IC technology include large ground-based, phased-array radar systems; flexible electronic countermeasures and electronic counter-countermeasures equipment; and terminally guided munitions.

As the Soviet Union accelerates the introduction of ICs into its military forces, these types of examples will multiply. On the basis of our analysis of VPK-assigned priorities for acquisition of Western technology and the stated military applications of these acquisitions, we believe that the Soviets place a high priority on inserting advanced Soviet-made microelectronics into their avionics, missile guidance, tank and artillery fire control, antisubmarine warfare, and intelligence systems. Microelectronics also has a cascading impact on the volume of weapons production. Robotics, numerical control, and flexible manufacturing are becoming more important in military production as part complexity increases.[4] Advances in these manufacturing technologies are all heavily dependent on microelectronics. Soviet improvements in these areas would serve not so much to increase the speed of production of any particular part but rather to bolster uniform production quality.

Outlook: What They Need and Will Therefore Try To Acquire

Soviet Microelectronics Needs for the Next Decade: Qualitative and Quantitative Improvements

To improve performance capabilities, the Soviet Union will continue to insert advanced microelectronics technology into new or upgraded military systems. This effort will be most apparent in major weapon subsystems, such as avionics, missile guidance, tank and artillery fire control, antisubmarine warfare, automated command and control, and intelligence systems. To meet their desired goals in these areas, we believe that the Soviets must improve their LSI production capabilities and at least develop moderate-level VLSI production capabilities. The Soviets reportedly intend to develop these types of VLSI capabilities by the early 1990s. Ideally, the Soviets probably hope to develop advanced VLSI capabilities and some ultralarge-scale integration (ULSI) capabilities by the mid-1990s, with ULSI capabilities maturing at and following the turn of the century. In addition, the Soviets will need to expand their production capacity for all types of ICs—or continue to acquire them in large volume—as more microelectronics are introduced into critical military-related systems.

To further develop its qualitative microelectronics capabilities in the VLSI area, we believe the USSR will need to radically improve its clean room technology, circuit design capabilities, feature resolution, thin-film quality, and automatic testing equipment. To progress to the advanced VLSI and ULSI levels, the USSR will also need to produce higher purity silicon with uniform doping and to develop advanced packaging and metalization techniques. To develop its quantitative capabilities, the Soviet Union needs to introduce more and better automated equipment into its production facilities. Advanced process control equipment is required to increase production uniformity and production yields. These needs—most of which will require Western technology acquisitions—are summarized in table 3.

Future Acquisitions: Critical Technology Targets

To improve their clean room technology and thereby increase device yields, the Soviets need to develop or acquire high-efficiency particulate air (HEPA) filters and the know-how required to use them in an overall clean room layout. Proper clean room design also involves early planning of optimum nonturbulent airflow patterns to keep whatever particulate contaminants that pass through the filters away from the wafer processing area. Beyond air filters and clean room design, the Soviets face a more difficult problem of disciplining their production workers to follow through with the annoying, time-consuming practices required to keep their clean rooms clean

For the Soviets, the most important requirement for improving circuit designs is the use of computer-aided design (CAD) equipment. Soviet capabilities are well behind Western standards and are inadequate to meet projected Soviet needs. As a result, we believe the USSR will place a high priority on acquiring this equipment from the West

To improve their feature resolution (a measure of circuit density) to the moderate VLSI level, the Soviets need to acquire better lithography and etching equipment. In particular, the Soviets probably will emphasize projection aligners and dry etchers. The Soviets' production capacity problems may initially cause them to acquire scanning projection aligners with high throughput and resolutions acceptable up to the 256K DRAM level. For more advanced applications such as 1- and 4-megabit DRAMs, however, the Soviets probably will concentrate on stepping projection aligners and electron-beam or X-ray exposure systems, all with submicron resolution capability. In etching, we believe the Soviets will seek reactive ion etching (RIE) and chemical plasma systems for etching silicon, nitrides, oxides, and resists, as well as ion milling systems for etching metals

To improve thin-film quality, the Soviets probably will concentrate on acquiring both epitaxial and non-epitaxial deposition equipment. This equipment will be needed to fabricate complex structures and thin, high-performance diodes and transistors. In epitaxial equipment the USSR will need almost all equipment types, but especially molecular-beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD). For nonepitaxial deposition the Soviets will seek low-pressure and plasma-enhanced CVD equipment (LPCVD and PECVD). In addition to work in silicon-based ICs, many of these techniques are also critical for developing and producing ICs based on compound semiconductors, such as gallium arsenide, that offer significant speed and radiation hardness improvements over silicon.

Table 3
Future Soviet Microelectronics Needs

Soviet Goal	Improvements Needed
Improve VLSI capabilities	Clean room technology Circuit design Feature resolution Thin-film quality Automatic testing
Develop advanced VLSI and ULSI capabilities	High-quality silicon Advanced metalization Advanced packaging
Increase production quantity	Automated equipment Process control
Insert state-of-the-art ICs into military systems	High-density memories High-speed 32-bit microprocessors Application specific ICs High-speed analog-digital and digital-analog converters

[ ] report that the Soviets are deficient in advanced automated test equipment. This deficiency reduces system reliability by making it difficult to test ICs adequately at the production stage. As a result, defective ICs are not found until they are assembled onto printed circuit boards and the boards fail to function. It also necessitates overproduction in order to compensate for high failure rates. To counter this, the Soviets probably will place a high priority on acquiring advanced VLSI-level integrated circuit testers, as well as wafer probe testers capable of testing LSI and VLSI ICs near their operating speeds. To meet optimum production needs [ ] believe that the Soviets need at least 170 VLSI-level IC testers, and would need four times as many LSI-level testers if VLSI testers were not available. Soviet needs for testers will increase dramatically as their volume production moves from the MSI/LSI level more to the VLSI level.

To improve circuit yields, especially for advanced VLSI and ULSI circuits, the Soviets need more silicon of a higher purity. To improve their silicon quality, the Soviets need automated crystal pullers, primarily those using the Czochralski method to grow uniformly doped monocrystalline ingots 5 inches in diameter or greater. The purity of this material must be improved, requiring better polycrystalline feedstock. In addition to acquiring better quality equipment, the Soviets will also need to expand their silicon production capacity by over one-third to meet what we estimate will be their needs in the early 1990s. The USSR might increase production facilities or equipment at its three known major polysilicon plants, but optimally would build a new polysilicon plant (probably in the eastern USSR to disperse its production base for strategic reasons). The Soviets will also require an expanded capacity to convert this polysilicon into monosilicon

As Soviet ICs move into the advanced VLSI range, the Soviets will encounter packaging and metalization problems similar to those now encountered in the West. Advanced VLSI and ULSI ICs will require several hundred terminals for external connections and will dissipate several watts of power. These factors combine to make packaging technology a limiting factor equal to feature resolution, the traditional limitation. As more and more functions are packed into one IC, metal interconnections will be placed more closely together and will be laid down in two or more layers. This is beyond current Soviet capabilities, and the Soviets will need advanced equipment and know-how to overcome this problem

To overcome slack quality control procedures and normal variations in human performance and to reduce particulates that cause device failure, the Soviets will emphasize automated equipment for the critical areas listed above. This emphasis on automated equipment will also require the Soviets to acquire new equipment for all process steps, not only those highlighted above. Acquisition of process control equipment probably will concentrate on parametric testers and materials characterization. This equipment would enable the Soviets to locate problem areas quickly when they occur on the wafer processing line

In addition to the acquisition of advanced production equipment for the production of VLSI-level ICs, we estimate the Soviets will have a continuing need to acquire finished ICs from the West. These will be used to meet consumption where indigenous production volume does not suffice and to provide state-of-the-art ICs that are beyond Soviet capabilities to produce. The most significant acquisitions will be high-density memory chips, high-speed microprocessors, application-specific ICs, and high-speed analog-to-digital and digital-to-analog converters.

US Programs of Special Interest to the Soviets: VHSIC and the SDI

For the last 15 years, US military microelectronics technology has followed civilian advances and has thus lagged consumer applications. The Soviet lag between development of new ICs and their application in fielded military systems has been shorter than that in the United States. The effect has been to reduce the Soviet military technology lag below the lag implied by the relative capabilities of Soviet versus US industry as a whole. This condition could be changing, however, because of two US military programs, VHSIC (very high-speed integrated circuits) and the SDI (Strategic Defense Initiative).

VHSIC is a Department of Defense program intended to insert the most advanced VLSI technology available from US industry into critical new weapon systems. Civilian production technology is currently being used, but the circuits developed will be more advanced than those commercially available and will be optimized for military uses, instead of being adapted from primarily civilian applications as is contemporary practice. As the VHSIC program progresses, it will push forward the state of the art in production technology, much as military programs pushed microelectronics technology in the early 1960s, and as commercial initiatives have pushed the technology since then. The ultimate goal of VHSIC is to apply the most advanced microelectronics available to all appropriate military systems. If this goal is reached, the impact will be to advance US military electronics capabilities. Because of VHSIC's military importance, we believe the USSR is focusing a large part of its technology acquisition program on VHSIC developments, both to advance Soviet capabilities and to assess the impact of VHSIC on US weapons

The SDI currently has a less direct effect on US military microelectronics than VHSIC, but it could become more significant in future programs. Industry experts believe that microelectronics will be one of the key enabling factors for space-based missile defense effectiveness, and that any development resulting from the SDI will require massive use of ULSI microelectronics and its computer technology derived therefrom. This would push the US microelectronics industry to achieve new breakthroughs, well beyond contemporary US—not to mention Soviet—capabilities. In addition to the likely massive intelligence collection program the Soviets already target against the SDI, they are likely to focus significant resources on microelectronics research deriving from the SDI.

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Appendix

Microelectronics Production: Sand to Circuits

Overview

Microelectronic integrated circuits (ICs) are used to perform a wide variety of electrical functions. These ICs duplicate—on a microscopic scale—electronic circuits that previously incorporated hundreds or thousands of individual, or "discrete," electronic components such as transistors, diodes, capacitors, and resistors. Fabricating these circuits on a microscopic scale increases system reliability and performance, while decreasing size and power requirements. In this appendix, we will describe the variety of physical and chemical processes required to fabricate an IC. Different ICs will require different combinations and permutations of these steps, but the fundamental process remains the same.

The basic microelectronics production unit is a thin disk of silicon called a wafer, which can contain hundreds of individual ICs. As more ICs are packed onto one wafer, the production process becomes more economical. Microelectronics production begins with making wafers from sand or quartz. Wafers are then put through a repetitive procedure in which a stencil-like mask is first patterned on the wafer, and then some physical process is accomplished to change the electrical properties of the exposed portions of the wafer. After this repetitive process is completed, the wafer is diced into hundreds of identical ICs, which are then packaged and tested. These key operations are known as crystal growth and wafer preparation, lithography, wafer processing, assembly, and testing (see figure 10)

Crystal Growth and Wafer Preparation

The basic material for almost all microelectronics is silicon. Silicon in its raw form is abundant, primarily as silicon dioxide. Before it can be used in microelectronics, however, it must be separated and purified in a procedure known as wafer fabrication. It is first processed into 99.999-percent pure "electronic-grade" polycrystalline silicon, or polysilicon, in which the internal structure is a mixture of all possible crystal orientations. This process is carried out in a furnace, and the finished polysilicon resembles rocks. These chunks of polysilicon are then melted in a crystal puller, which inserts a "seed" of the desired crystal orientation into the melt and pulls it out slowly, allowing the molten silicon to solidify on the seed. It is pulled in the form of a cylinder called a boule. After this pulling process, the internal structure of the boule has a uniform crystal orientation and is known as monocrystalline silicon, or monosilicon. The boule is sliced into disks called wafers, which are lapped to the desired thickness and polished to produce an almost perfectly flat surface.

Lithography

In lithography, a circuit designer uses a computer-aided design (CAD) system to design the electrical circuit desired and to translate that idealized electrical representation into a multilevel physical IC layout. A chemical layer called a resist that is sensitive to the radiation source to be used—visible light, ultraviolet light, electron beams, X-rays, or ion beams—is applied to the wafer. One level of the IC is patterned onto the resist using proximity aligners (old technology), scanning or stepping projection aligners (standard technology), electron-beam systems (advanced technology), X-ray aligners (research stage technology), or ion-beam systems (exploratory research). Either the exposed resist or the unexposed resist is washed away, enabling a wafer processing step to be carried out on the desired portions of the underlying layer.

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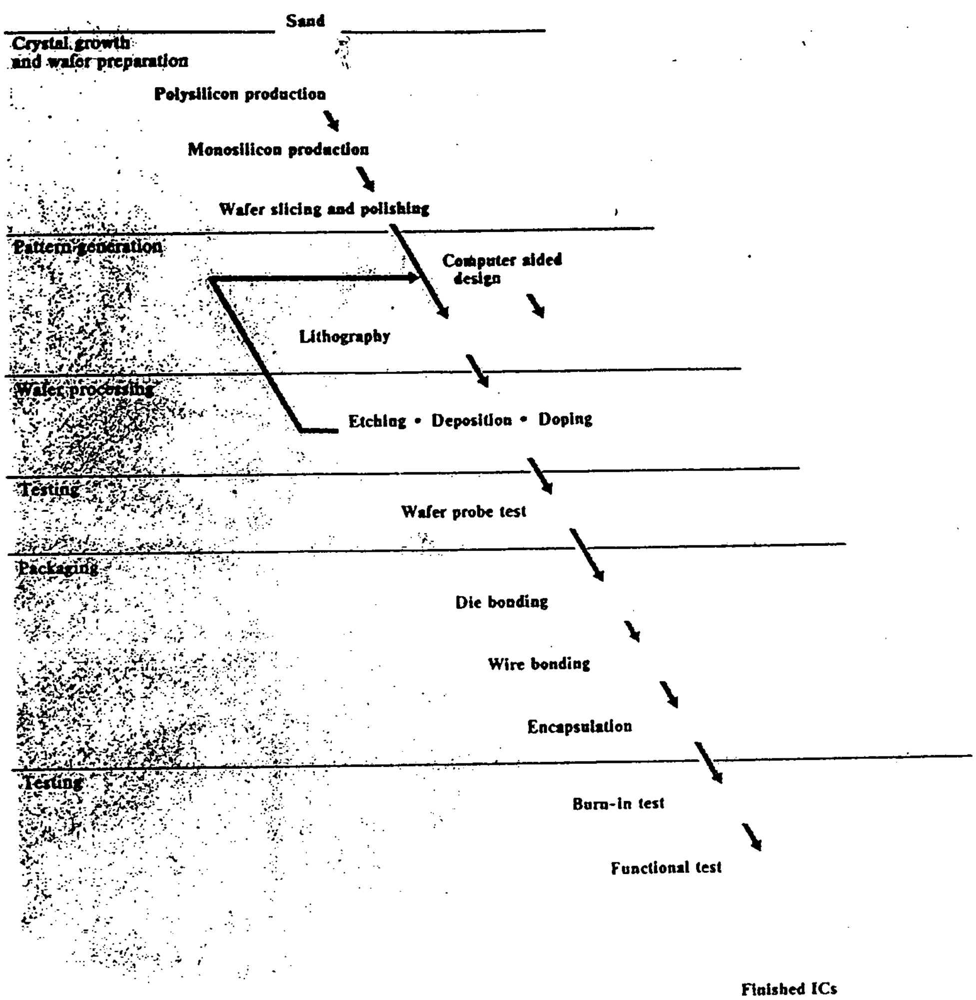
Figure 10
Microelectronics Production Process Flow



Wafer Processing: Etching, Deposition, and Doping

Etching

Etching is a process in which portions of the wafer surface revealed during lithography are selectively removed. The two basic types of etching are wet (acid) etching and dry etching. Wet etching is the older type and is still used for relatively simple ICs with line widths greater than 3.5 microns. Wet etching cannot be used much below that feature size because of its tendency to etch sideways at the same time as it etches downward, causing the lines to spread and merge together. To overcome this drawback, dry etching is used for advanced ICs. The major dry techniques are chemical plasma etching, ion milling, reactive ion etching, and reactive ion-beam etching. Each has different characteristics of throughput, spread, and material selectivity. Current dry-etching systems are capable of etching lines down to about 0.2 microns wide, far beyond what current IC designs require

Deposition

Deposition can be divided into two categories, epitaxial and nonepitaxial. Epitaxial growth is the most difficult to achieve, and requires that the crystal structure of the wafer be continued through the deposited layer. The three basic types of epitaxy are liquid-phase epitaxy (LPE), vapor-phase epitaxy (VPE), and molecular-beam epitaxy (MBE). LPE is the oldest technique and has been overtaken by the popular VPE, which includes metal-organic chemical vapor deposition (MOCVD). MBE is the most advanced technique and produces the best results in terms of sharp doping profiles and utility for exotic III-V and II-VI compound semiconductor materials.

Nonepitaxial chemical vapor deposition (CVD) and physical vapor deposition (PVD) are less demanding processes. The four basic types of nonepitaxial CVD are atmospheric, low pressure (LPCVD), plasma enhanced (PECVD), and photochemical (PCVD). CVD can be used to deposit many materials, but those generally encountered (other than epitaxial silicon) are polycrystalline silicon, silicon dioxide, and silicon nitride. PVD is used to deposit thin layers of metals or silicides on the wafer to act as interconnects between individual devices on each IC. The two methods of PVD are evaporation and sputtering. Evaporation is the conventional method for metal deposition, but it has been replaced by sputtering in advanced applications. The major drawbacks to evaporation are the difficulty in controlling alloy composition and the nonuniform coverage of steps on the wafer surface. Evaporators are classified by the method of evaporation: filament, electron beam, flash, and induction. Sputtering is often the deposition method of choice because of its ability to produce high-quality films at a high rate of growth and at lower temperatures. The basic types of sputtering systems are electron beam, diode, triode, and magnetron

Doping

Doping is the controlled introduction of precise quantities of impurities, or dopants, into certain portions of the wafer in order to achieve desired electrical characteristics. The conventional doping system is a diffusion furnace, which relies on heat to spread dopants steadily from the wafer surface into the depths of the wafer. The other, more recent technique is ion implantation, which is the direct injection of dopant atoms into the wafer. One of the major advantages of implantation over diffusion is better control of doping profiles because of lower process temperatures. The two most important characteristics of implantation are: (a) dose—the number of ions that reach the wafer, which is controlled by beam current; and (b) junction depth—the depth beneath the surface where the ions stop, which is controlled by beam energy. Ion implanters, which are classified by current and energy, have three categories: medium current, high current, and high energy.

Assembly

Assembly is the step following wafer processing. After the individual ICs—or die—on the wafer are sawed apart, the functional parts (see testing section) are attached to a package in the die-bonding step. The three types of die bonding are eutectic, preform, and epoxy. Die bonding is followed by wire bonding, which is the major method used to connect the die electrically to terminals leading outside the package. Other techniques include flip-chip, solder bump, beam lead, and film bonding, but none of these has replaced wire bonding. The final step is encapsulation, during which the IC is enclosed in plastic or ceramic

Testing

Testers can be divided into two categories, wafer probe and packaged IC. The wafer probe tester is used for rapid testing of dice on wafers. A small number of tests are made, but not at the circuit's operating speed. The purpose of the test is to mark bad die *before* time and money are invested in packaging. Packaged IC testers can be divided into burn-in systems and functional testers. Burn-in systems are used to identify quickly the parts that would fail soon after they are first used. Batches of ICs are loaded into a temperature- and humidity-controlled chamber, powered up, and allowed to sit for a length of time to simulate longer term normal use. Most weak parts fail at this stage, increasing the reliability of the systems that will use those ICs that pass the burn-in test. This testing is especially important in military equipment. Functional testers are used to verify that an IC works properly at its intended operating speed. These testers are usually classified by the highest level of integration able to be handled; for example, MSI, LSI, or VLSI. VLSI testers require extensive computing power and software packages, which must be updated for each new product development, causing these systems to resemble highly advanced computers more than testers